MAGMA RESERVOIR FAILURE: IMPLICATIONS FOR VOLCANO GROWTH ON VENUS AND MARS

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Overview: Data obtained from a numerical model of magma reservoir failure, combined with observational constraints, provide insight into the conditions which promote volcano growth on Venus and Mars. On Venus, gradual deepening of an oblate ellipsoidal reservoir in a host rock subjected to uniaxial strain is consistent with the eruptive sequence preserved at Sapas Mons; further work is required to determine if this sequence is representative of other venusian edifices. On Mars, however, many eruptive sequences are known to be similar. These are most consistent with the presence of an oblate ellipsoidal reservoir located in a host which relaxes from uniaxial strain to lithostatic stress over time.

Introduction: Observational evidence, including calderas and laterally extensive dike swarms, indicates that magma reservoirs exist beneath and have fed many large volcanic edifices on Venus and Mars [1,2]. Understanding the mechanical evolution of the reservoirs can therefore provide insight into how these volcanoes develop and grow. The interplay between and relative importance of the factors which control reservoir failure, however, is not yet well understood. Excess pressure derived from repeated magma injection is uniform throughout the reservoir and thus, while this pressure may drive fracturing, other factors must dictate where the reservoir wall fails. Recent studies [3,4], building upon earlier efforts (*e.g.*, [5-7]), have identified a number of different factors which may control the point at which a reservoir fails; however, no published model explicitly incorporates them all, and conflicting conclusions are often drawn. Using a numerical model which incorporates all the parameters identified by earlier authors, we systematically re-evaluate how these factors contribute to reservoir failure [8]. Here we briefly summarize the results and, through comparison with observations from Venus and Mars, consider possible implications for edifice growth on each planet.

Model: Using an axisymmetric finite element method, we treat the reservoir as an internally pressurized ellipsoid within an elastic host. The left hand boundary of the mesh, which defines the rotation axis of the system, is free to slip in the vertical direction. The upper surface is pinned at the right end to anchor the mesh but is otherwise free, while depth-dependent vertical and horizontal forces, respectively, are applied to the bottom and right hand sides of the region to create a reference state of stress in the host rock. Forces applied normal to the reservoir walls reflect both excess pressure and a hydrostatic term. The program evaluates stresses for each element in polar cylindrical coordinates, then calculates the stresses normal and parallel to the reservoir walls to determine where tensile failure first occurs.

Summary of Results: The point at which failure first occurs, summarized in Table 1, is controlled primarily by the interaction between three parameters. These are: (a) the reference state of stress in the host rock; (b) the aspect ratio of the reservoir; and, (c) the size of the reservoir relative to its depth below the surface. Compared to these, the density difference between host rock and magma as a function of depth, even under extreme non-neutral buoyancy conditions, has only a minimal impact upon the failure location.

For a spherical magma body within a host rock subjected to either uniaxial strain or lithostatic stress, the most common point of failure is near the crest of the reservoir. This should promote vertical dike emplacement and centralized eruptions. Under lithostatic conditions, however, increasing the reservoir's proximity to the surface promotes rotation of the failure point away from the crest, producing stresses more consistent with either ring dike or cone sheet intrusion.

If a magma body approximates an oblate ellipsoid, the host rock stress state becomes more important. When the host is subjected to lithostatic stress, the reservoir always fails near its midpoint. (Note that sill injection is favored over lateral (radial) dike intrusion, contrary to results reported elsewhere [4].) But, when the host rock is subjected to uniaxial strain an oblate reservoir continues to fail near its crest. Mathematically, this location is only weakly favored relative to all other points on the reservoir wall. In practice, failure may therefore occur nearly anywhere in response to subtler effects than those we have treated. Irrespective of where failure takes place, however, dike injection is favored, and thus anything from vertical dikes feeding central eruptions to lateral dike intrusion can plausibly occur.

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TABLE 1: Point of Failure in Degrees of Arc Relative to Top of Chamber and Possible Intrusion Style						
HOST ROCK STRESS STATE		RESERVOIR SHAPE				
&		Spherical			DEPTH	Oblate
RESERVOIR DEPTH		Host Rock Density Model				Density Model
		Uniform	2-Layer	Gradual Δ (*)		Gradual Δ (*)
Uniaxial Strain	Shallow	0° vertical dike	0° vertical dike	0° vertical dike	Shallow	0 - 90° dike
	Deep	0° vertical dike	0° vertical dike	0° vertical dike	Deep	0° vertical dike
Lithostatic Stress	Shallow	45° ring dike; cone sheet	30° ring dike; cone sheet	45° ring dike; cone sheet	Shallow	90° lateral sill
	Deep	0° vertical dike	0° vertical dike	0° vertical dike	Deep	90° lateral sill
(*) Host density follows exponential form reflecting compaction of basaltic material (see *Head & Wilson* , 1992)						

Discussion: On Mars, many of the volcanoes exhibit a common eruptive sequence [9]. Initial edifice construction occurs upon a thick accumulation of pre-edifice plains via persistent centralized eruption from a deep-seated magma reservoir. Eventually, however, the locus of eruption switches from a point near the summit to multiple flank locations. This sequence eliminates uniaxial strain and a spherical reservoir as well as lithostatic stress and an oblate reservoir, as neither combination facilitates the observed transition in eruption style. The sequence of events is consistent with, however, either variation in reservoir depth relative to the summit as the volcanoes grow or changes in the host rock state of stress as a function of time; in either instance the presence of an oblate reservoir is implied. (Note: The possible role played by edifice stresses is discussed elsewhere [10].) If reservoir depths change, they must grow shallower with time. It is unlikely, however, that reservoirs move to shallow enough depths for rotation from vertical to lateral failure to occur, as both observational evidence and theoretical calculations suggest that reservoirs on Mars form and remain at great depth [2,11]. It is perhaps more plausible, therefore, that a change in the host rock stress from a condition of uniaxial strain to a situation more closely approximating lithostatic is consistent with the observed sequence of eruptive events at volcanoes on Mars.

On Venus, fewer eruptive sequences have been rigorously evaluated. Here we consider the sequence documented at Sapas Mons [12], where early emplacement of lateral dikes and numerous flank eruptions were gradually superseded by centralized eruptions. Within the context of our modeling results, the observed variation in the eruptive sequence cannot be produced by either uniaxial strain and a spherical reservoir or by lithostatic stress and an oblate reservoir; furthermore, lateral diking is quite inconsistent with a spherical reservoir and lithostatic stress. The entire sequence can be explained by an oblate reservoir subjected to uniaxial strain, however, provided that the reservoir deepens relative to the summit of the volcano as the edifice grows. This interpretation suggests that uniaxial strain persistently defined the reference state of stress beneath Sapas Mons as it formed. Intriguingly, one way uniaxial strain could occur is if lava erupted at the surface gets buried beneath subsequent deposits, a situation broadly consistent with the process of plains emplacement on Venus. In addition, the oblate geometry inferred for the reservoir and its relative deepening as the edifice grows are both consistent with theoretical predictions [1]. To better constrain our model results and the reference state of stress beneath venusian edifices in general, however, we need to know whether the eruptive sequence at Sapas Mons is typical of other volcanoes, and we need to derive new ways to constrain the subsurface geometry of magma reservoirs using surface observations.

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